

Limiting the Effective Mass and New Physics Parameters from $0\nu\beta\beta$

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In the light of the recent result from KamLAND-Zen (KLZ) and GERDA Phase-II, we update the bounds on the effective mass and the new physics parameters, relevant for neutrinoless double beta decay ($0\nu\beta\beta$). In addition to the light Majorana neutrino exchange, we analyse beyond standard model contributions that arise in Left-Right symmetry and R-Parity violating supersymmetry. The improved limit from KLZ constrains the effective mass of light neutrino exchange down to sub-eV mass regime 0.06 eV. Using the correlation between the ^{136}Xe and ^{76}Ge half-lives, we show that the KLZ limit individually rules out the positive claim of observation of $0\nu\beta\beta$ for all nuclear matrix element compilation. For the Left-Right symmetry and R-parity violating supersymmetry, the KLZ bound implies a factor of 2 improvement of the effective mass and the new physics parameters. The future ton scale experiments such as, nEXO will further constrain these models, in particular, will rule out standard as well as Type-II dominating LRSM inverted hierarchy scenario.

Introduction— The experimental observations of neutrino mass and mixing have opened a new window to physics beyond the standard model (SM). So far, the solar and atmospheric mass square differences (Δm_{21}^2 and Δm_{31}^2), the three oscillation angles θ_{12} , θ_{23} and θ_{13} have been measured to a moderate degree of precision [1]. The remaining open questions in the leptonic sector, that still need to be answered are: the neutrino mass hierarchy and the lightest neutrino mass scale, the CP-violating phases and the fundamental nature of SM neutrinos - if they are Dirac or Majorana particle. The Majorana mass of the light neutrinos violates lepton number conservation, and hence, this can be determined by observing lepton number violating (LNV) signature in neutrinoless double beta decay ($0\nu\beta\beta$) $(A, Z) \rightarrow (A, Z - 2) + 2e^-$ [2].

In a concrete model that generates viable neutrino mass and mixing, beyond standard model (BSM) states carrying LNV can also directly mediate $0\nu\beta\beta$. These additional contributions have been widely discussed in the literature [3], in particular, for Left-Right symmetry (LRSM) ([4] and [5–15]), for R-parity violating supersymmetry (RPV) [16–24], and for other scenarios [25, 26]. The BSM states of mass within a few tens of TeV can significantly contribute to $0\nu\beta\beta$ [9, 22, 23, 26] and saturate the present experimental limits, while being in accordance with the collider [22, 23, 27–37] and cosmological bounds [38].

Several experimental searches have been carried out till date to look for the signal in $0\nu\beta\beta$. The recent bound on the half-life of ^{136}Xe as reported by KamLAND-Zen $T_{1/2}^{0\nu} = 1.07 \times 10^{26}$ yrs (90% C.L.) [39] provides almost one order of magnitude improvement compared to the previous bounds: $T_{1/2}^{0\nu} = 1.9 \times 10^{25}$ yrs (KLZ 90% C.L.) [40], $T_{1/2}^{0\nu} = 1.6 \times 10^{25}$ yrs (EXO-200 90% C.L.) [41], $T_{1/2}^{0\nu} = 3.4 \times 10^{25}$ yrs (KLZ+EXO 90% C.L.) [40]. The present limit on the half-life of ^{76}Ge is $T_{1/2}^{0\nu} = 5.2 \times 10^{25}$ yrs (GERDA Phase-II 90%) [42].

The previous limits are $T_{1/2}^{0\nu} = 2.1 \times 10^{25}$ yrs (GERDA 90%) and $T_{1/2}^{0\nu} = 3.0 \times 10^{25}$ yrs (GERDA+Heidelberg-Moscow+IGEX 90%) [43]. There has been only one claim of observation of $0\nu\beta\beta$ with the half-life $T_{1/2}^{0\nu} = 2.23_{-0.31}^{+0.44} \times 10^{25}$ yrs (68% C.L.) [44], which has been significantly constrained by the the measurements from GERDA and KLZ [9, 42].

In the light of the recent KamLAND-Zen result [39] and result from GERDA Phase-II [42], we re-analyze the different contributions in $0\nu\beta\beta$ that arise in LRSM and RPV susy scenarios. We consider both the canonical light neutrino and BSM exchange mechanisms in $0\nu\beta\beta$, such as a) right handed (RH) gauge boson and right handed neutrino exchange in LRSM and b) sbottom and gluino exchange in RPV susy and derive the updated limits on the relevant parameters. In addition, we re-check the validity of the positive claim of observation against the null result of KLZ and show that assuming the light neutrino exchange as the only mechanism of $0\nu\beta\beta$, the recent KLZ limit completely rules out the positive claim of observation of $0\nu\beta\beta$ for all nuclear matrix elements (NMEs), and so do the new limit from GERDA Phase-II. For LRSM and RPV susy, we further explore the prediction of these theories in future ton-scale experiments, such as, nEXO.

Left-Right Symmetry: The Left-Right symmetry [4] is one of the most appealing renormalizable framework, that can explain light neutrino mass and mixing via a combination of Type-I [45] and Type-II Seesaw [46]. The model consists of the $SU(2)_L$ doublets - $Q_L \equiv (u \ d)_L^T$ and $\psi_L \equiv (\nu_\ell \ \ell)_L^T$, $SU(2)_R$ doublets $Q_R \equiv (u \ d)_R^T$ and $\psi_R \equiv (N_R \ l_R)_R^T$. The Higgs sector of the model consists of a bidoublet Φ and $SU(2)_{L(R)}$ -triplets $\Delta_{L(R)}$. The generic Yukawa Lagrangian of the model is given by

$$\begin{aligned} \mathcal{L}_Y = & h_q \bar{Q}_L \Phi Q_R + \tilde{h}_q \bar{Q}_L \tilde{\Phi} Q_R + h_l \bar{\psi}_L \Phi \psi_R + \tilde{h}_l \bar{\psi}_L \tilde{\Phi} \psi_R \\ & + f_L \psi_L^C \Delta_L \psi_L + f_R \psi_R^C \Delta_R \psi_R + \text{H.c.} \end{aligned} \quad (1)$$

In the above, C denotes charge conjugation operator

and $\tilde{\Phi} = \tau_2 \Phi^* \tau_2$, where τ_2 is the second Pauli matrix. The above Lagrangian generate the Dirac mass of the light neutrinos after electroweak symmetry breaking by the bidoublet vacuum expectation value (VEV) $\langle \Phi \rangle = \text{diag}(\kappa, \kappa')$, $M_D = h_l \kappa + \tilde{h}_l \kappa'$. The triplet VEVs of $\langle \Delta_{L,R}^0 \rangle$ (denoted as $v_{L,R}$) generate the Majorana mass terms of light neutrino and heavy neutrino $m_L = f_L v_L$ and $M_R = f_R v_R$, respectively. In the seesaw approximation, the light neutrino mass matrix

$$M_\nu \simeq m_L - M_D M_R^{-1} M_D^T. \quad (2)$$

In the above, the first and second terms represent the Type-II (Type-I) seesaw contributions. One of the simplistic possibility is the Type-II seesaw dominance in the light neutrino mass matrix that leads to $M_\nu \sim f_L v_L = v_L M_R / v_R$. This occurs as a consequence of $f_L = f_R$ (or $f_L = f_R^*$), which can be realized as an artifact of parity (charge conjugation) symmetry of the Lagrangian. The other regime of Type-I seesaw dominance can be realized for vanishingly small triplet vev $v_L \sim 0$, and the light neutrino mass in this case is $M_\nu \simeq -M_D M_R^{-1} M_D^T$.

Neutrinoless Double Beta Decay– In LRSM several new contributions arise that are mediated by the RH gauge boson, RH neutrino and Higgs triplet [5, 47, 48]. The half life $T_{1/2}^{0\nu}$ is given by:

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} g_A^4 \left| \sum_i \mathcal{M}_i \eta_i \right|^2, \quad (3)$$

where $G_{0\nu}$ is the phase space factor, g_A is the nucleon axial-vector coupling constant, \mathcal{M}_i represents the NMEs for the different exchange processes, and η_i are the corresponding dimensionless particle physics parameters. Below, we discuss different contributions.

- **Standard light neutrino exchange:** The light neutrino, if Majorana, can mediate the $0\nu\beta\beta$ process. The dimensionless parameter is,

$$\eta_\nu = \frac{1}{m_e} \sum_i U_{ei}^2 m_i = \frac{m_{ee}^\nu}{m_e}, \quad (4)$$

where m_{ee}^ν is the effective mass for light neutrino exchange and m_e is the electron mass.

- **RR contribution:** The contribution from W_R and N_R exchange is one of the dominant contribution in $0\nu\beta\beta$, that depends only on the masses of the intermediate states and the gauge coupling. For a generic $g_R \neq g_L$, and generic RH neutrino mass the dimensionless parameter is (see [49] and [50] for the validity of this expression):

$$\eta_{N_R}^R \sim m_p \left(\frac{g_R}{g_L} \right)^4 \left(\frac{M_{W_L}}{M_{W_R}} \right)^4 \sum_i \frac{V_{ei}^{*2} M_i}{|p^2| + M_i^2}. \quad (5)$$

In the above, V_{ei} are the elements of the unitary matrix that diagonalizes the RH neutrino mass matrix M_R with eigenvalues M_i , $|p| \sim 100$ MeV is the typical momentum exchanged scale of $0\nu\beta\beta$ with $|p^2| = m_e m_p \frac{\mathcal{M}_N}{\mathcal{M}_\nu}$. Here, m_e , m_p are the masses of electron and proton, \mathcal{M}_ν and \mathcal{M}_N are the NME corresponding to the light and heavy neutrino exchange, respectively.

- **LL contribution:** The $W_L - N - W_L$ mediated LL contribution for generic mass M_i , smaller or larger than the momentum exchange scale is

$$\eta_{N_R}^L = m_p \sum_i \frac{S_{ei}^2 M_i}{|p^2| + M_i^2}. \quad (6)$$

where S_{ei} is the element of the active-sterile mixing matrix.

In addition, few other contributions that depend on the $W_L - W_R$ mediation/mixing can significantly contribute for large contribution to $0\nu\beta\beta$ [8]. They are:

- **λ contribution:** The light neutrino, W_L and W_R mediated λ contribution can be large for large active-sterile neutrino mixing T . The relevant dimensionless parameter is:

$$\eta_\lambda = \left(\frac{M_{W_L}}{M_{W_R}} \right)^2 \sum_i U_{ei} T_{ei}^*, \quad (7)$$

- **η contribution:** The light neutrino mediated η contribution depends on the $W_L - W_R$ mixing parameter ξ and can be large for large ξ [7, 10]. The dimensionless parameter is

$$\eta_\eta = \tan \xi \sum_i U_{ei} T_{ei}^*, \quad (8)$$

Note that, for TeV scale RH neutrino, their contribution in λ and η diagrams are small and can be ignored.

- **Triplet exchange:** The corresponding dimensionless parameter for right triplet exchange is

$$\eta_{\Delta_R} = \frac{m_p}{G_F^2} \frac{\sum_i V_{ei}^2 M_i}{M_{W_R}^4 m_{\Delta_R}^2}, \quad (9)$$

where M_i are the masses of the RH neutrino and m_{Δ_R} is the mass of the RH doubly charged Higgs triplet. The RH triplet of mass comparable or lower than the RH neutrino can give significant contribution in $0\nu\beta\beta$ that together with LFV processes can significantly constrain the quasi-degenerate regime [11]. The left handed triplet contribution is proportional to the light neutrino masses and therefore small. Hence, we do not consider this into our compilation.

NME			$ m_{ee}^\nu $	$ m_{ee}^\nu $
Method	$\mathcal{M}^{0\nu}_{(^{76}\text{Ge})}$	$\mathcal{M}^{0\nu}_{(^{136}\text{Xe})}$	(^{76}Ge)	(^{136}Xe)
EDF(U)[52]	4.6	4.2	0.20	0.06
ISM(U) [53]	2.81	2.19	0.33	0.12
IBM-2 [54]	5.42	3.33	0.17	0.08
pm-QRPA(U)[55]	5.18	3.16	0.18	0.08
SRQRPA-B[56]	5.82	3.36	0.16	0.08
SRQRPA-B[56]	4.75	2.29	0.20	0.11
QRPA-B [57]	5.57	2.46	0.17	0.11
QRPA-A[57]	5.16	2.18	0.18	0.12
SkM-HFB-QRPA [58]	5.09	1.89	0.18	0.14

TABLE I. The limits on the effective mass $|m_{ee}^\nu|$ for light neutrino exchange, that satisfy the KLZ bound $T_{1/2}^{0\nu} = 1.07 \times 10^{26}$ yrs [39] and the limit from GERDA Phase-II $T_{1/2}^{0\nu} = 5.2 \times 10^{25}$ yrs [59].

Following the recent limit of half-life $T_{1/2}^{0\nu}$ from KLZ [39], we show the bound on the effective mass parameter for standard light neutrino exchange mechanism in Table I. We adopt the phase space factor from [51], and include the NME uncertainties in our compilation [52–58]. Additionally, we also show the limits from GERDA Phase-II [42, 59]. The recent KLZ limit constrains the effective mass $|m_{ee}^\nu|$ in the sub-eV regime $m_{ee}^\nu \leq 0.06–0.14$ eV, almost a factor of 2 improvement as compared to the previous limit [9].

Till date, there has been only one claim of observation of $0\nu\beta\beta$ [44] for ^{76}Ge . The limit from GERDA Phase-II rules out the positive claim decisively. The validity of the positive claim has been judged against the previous null result of KLZ and this has been shown that for all but one NME, the KLZ+EXO-200 combined limit rules out the positive claim [9]. With the recent updated limit in hand, we re-check the validity of the positive claim against the null result of KLZ. In Fig. 1, we show the variation of the predicted half-life for ^{76}Ge vs the half-life ^{136}Xe . The ratio of these two half-lives depend on the NME uncertainty and the phase space factor $G_{0\nu}$:

$$\frac{T_{1/2}^{0\nu}(^{76}\text{Ge})}{T_{1/2}^{0\nu}(^{136}\text{Xe})} = \frac{G_{0\nu}(^{136}\text{Xe})\mathcal{M}_{^{136}\text{Xe}}^2}{G_{0\nu}(^{76}\text{Ge})\mathcal{M}_{^{76}\text{Ge}}^2} \quad (10)$$

The different colored lines and the light purple region represent the predicted half-life for ^{76}Ge . The horizontal grey band represents the positive claim of observation of $0\nu\beta\beta$ in ^{76}Ge [44]. The right most dashed vertical black line represent the most recent bound from KLZ. The other two vertical black lines represent the previous limits from KamLAND-Zen and the combined limit from KamLAND-Zen+EXO-200 [40]. Note that, while the previous individual limit from KLZ $T_{1/2}^{0\nu} = 1.9 \times 10^{25}$ yrs didn't rule out the positive claim completely, the most recent improved limit decisively rules out the positive

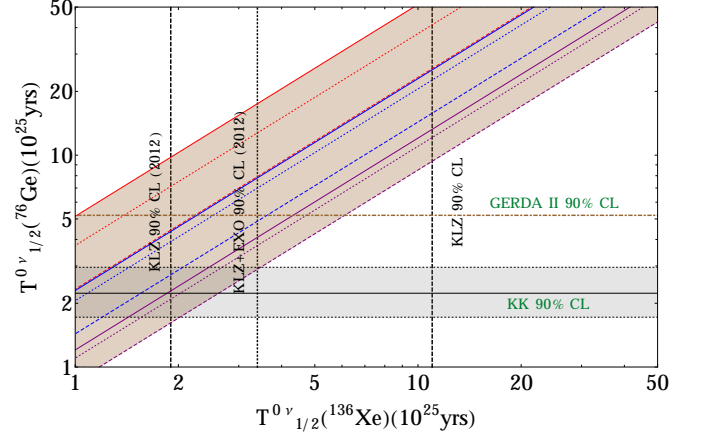


FIG. 1. The half-life $T_{1/2}^{0\nu}(^{76}\text{Ge})$ vs $T_{1/2}^{0\nu}(^{136}\text{Xe})$. The brown shaded region represents the effect of NME uncertainty. The gray horizontal band represents the positive claim. The vertical lines represent the recent KLZ limit and the older KLZ limit, KLZ+EXO combined limit. The horizontal brown dot-dashed line represents the present limit from GERDA Phase-II [42].

claim for all the NME compilations [52–58].

In Fig. 2, we show the half-life $T_{1/2}^{0\nu}$ corresponding to the light neutrino exchange by the yellow shaded region. The orange solid and the green dashed horizontal lines represent the KLZ limit $T_{1/2}^{0\nu} = 1.07 \times 10^{26}$ yrs [39] and the projected sensitivity of future ton-scale experiment nEXO $T_{1/2}^{0\nu} = 6.6 \times 10^{27}$ yrs [60]. The vertical lines correspond to the stringent limit from PLANCK [38] and KATRIN [61]. Note that, the new result from KLZ leaves only a small parameter space (the upper triangle at KLZ and KATRIN bounds crossing point) to be probed in KATRIN. The nEXO can exhaust even more parameter space which is still allowed by PLANCK and can rule out the standard IH for all values of light neutrino mass.

In addition to the canonical light neutrino contribution, we also consider the RR contribution and show the prediction in the same figure, where we assume a Type-II dominance in the light neutrino mass matrix [5]. For illustrative purpose, we consider a benchmark where the heaviest of the three RH neutrino $M_> = 1$ TeV and the RH gauge boson has masses $M_{W_R} = 3, 3.5$ and 4 TeV. We vary the lightest light neutrino mass from 10^{-8} eV. The light green band covered by red dash-double-dot lines in the figure represents the RR exchange contribution. The area between dot-dashed blue lines that is shaded in deep green represents the total contribution that arises from the light neutrino exchange and the heavy neutrino-right handed gauge boson exchange. The KLZ result rules out significant amount of parameter space. For NH scenario, the lightest RH neutrino $M_<$ in between 0.52 MeV– 72.3 GeV, 0.93 MeV– 41.1 GeV, and 1.77 MeV– 25.4 GeV are ruled out for $M_{W_R} = 3, 3.5,$

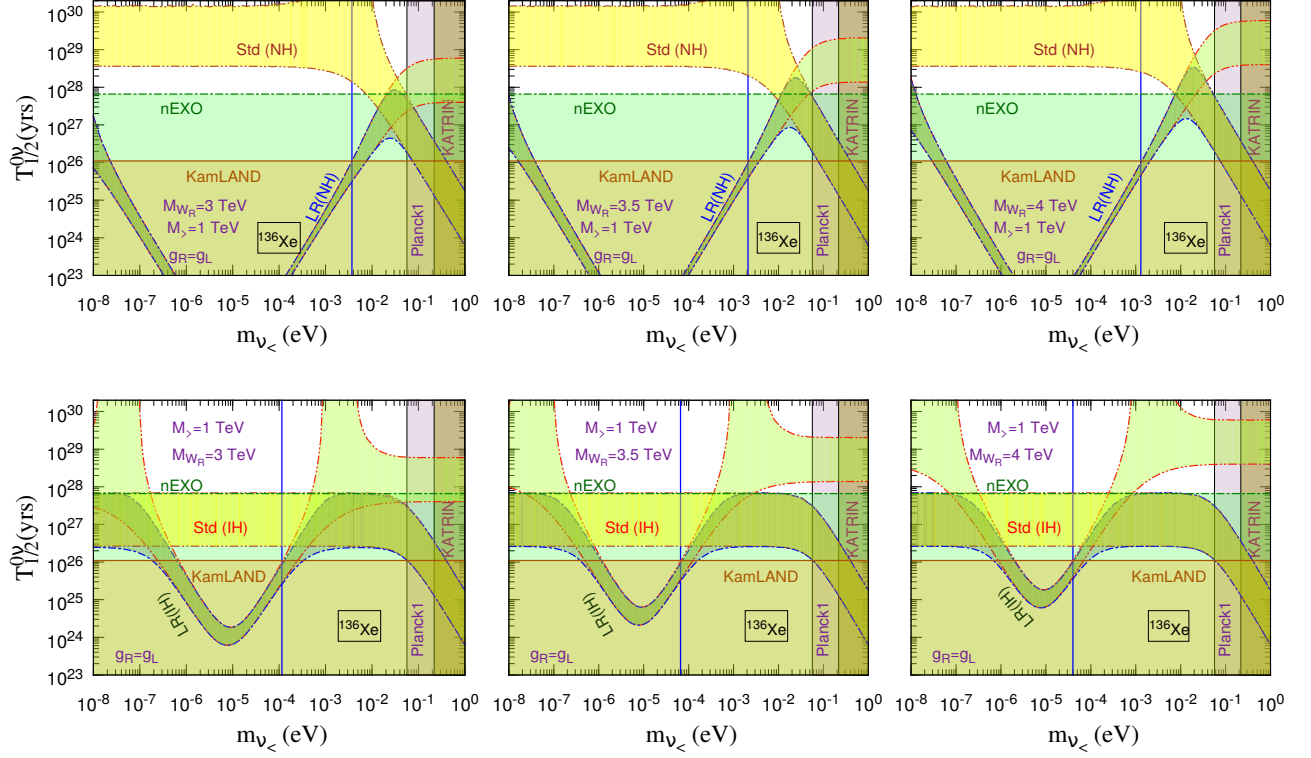


FIG. 2. The half-life $T_{1/2}^{0\nu}$ vs the light neutrino mass for NH (upper panel) and for IH (lower panel) for different W_R masses. The area between blue dot-dashed lines represents the total contributions (standard light neutrino+ heavy neutrino exchange) for Type-II dominance.

NH				
M_{W_R}	3 TeV	3.5 TeV	4 TeV	
$g_R = g_L$				
$m_{\nu_<} \text{ (eV)} \gtrsim$	3.7×10^{-3}	2.1×10^{-3}	1.3×10^{-3}	
$M_{\nu_<} \text{ (GeV)} \gtrsim$	72.3	41.1	25.4	
$m_{\nu_<} \text{ (eV)} \lesssim$	2×10^{-8}	4×10^{-8}	8×10^{-8}	
$M_{\nu_<} \text{ (MeV)} \lesssim$	0.52	0.93	1.77	
IH				
M_{W_R}	3 TeV	3.5 TeV	4 TeV	
$g_R = g_L$				
$m_{\nu_<} \text{ (eV)} \gtrsim$	1.2×10^{-4}	6.6×10^{-5}	4×10^{-5}	
$M_{\nu_<} \text{ (GeV)} \gtrsim$	2.25	1.3	0.78	
$m_{\nu_<} \text{ (eV)} \lesssim$	6.5×10^{-7}	1.2×10^{-6}	2×10^{-6}	
$M_{\nu_<} \text{ (MeV)} \lesssim$	12.8	23.6	39.3	

TABLE II. The limits on the lightest neutrino mass $m_{\nu_<}$ and the lightest RH neutrino mass $M_{\nu_<}$, that come from KLZ, assuming a Type-II dominance in the lightest neutrino mass.

and 4 TeV, respectively. Similarly, for IH scenario, the ruled out mass ranges are 12.8 MeV-2.25 GeV, 23.6 MeV-1.3 GeV, and 39.3 MeV-0.78 GeV. A summary of these results is also given in Table-II. For $g_R \neq g_L$, still as-

suming $f_L = f_R$ for simplicity, the result resembles to Fig. 2. The summary of the results for this scenario of $g_R = 0.5 \neq g_L$ is given in Table-V (see the Appendix).

For the $0\nu\beta\beta$ process mediated by the heavy RH neutrinos the energy scales at which effective interactions are generated and the scale at which the process are measured can be different. The QCD correction in the RG running and color mismatch due to these corrections may lead to substantial correction in $0\nu\beta\beta$ decays [62–64]. In Ref. [64], the authors have calculated the leading QCD corrections to the complete set of short range $d = 9$ $0\nu\beta\beta$ operators. For few of the operators the corrections can be large by order of magnitude. However, for LR model, the corresponding operator ($|C_3(\Lambda)|$) leads to small correction (see TABLE-II of [64]) to make any significant difference in our conclusions.

The future ton scale experiment nEXO will completely rule out any distinguishable NH BSM signature for the scenario $M_{\nu_>} = 1$ TeV and $M_{W_R} \leq 4$ TeV of Type-II dominance. In the IH scenario there is very limited scope to probe distinguishable Type-II dominant BSM physics in nEXO, that has yet not been ruled out by KLZ. Both the canonical or RR IH scenario can be completely ruled out by nEXO for even higher W_R masses. Thus, may play a decisive role in fixing the mass hierarchy. For the other contributions in LRSM that emerge from Type-I dom-

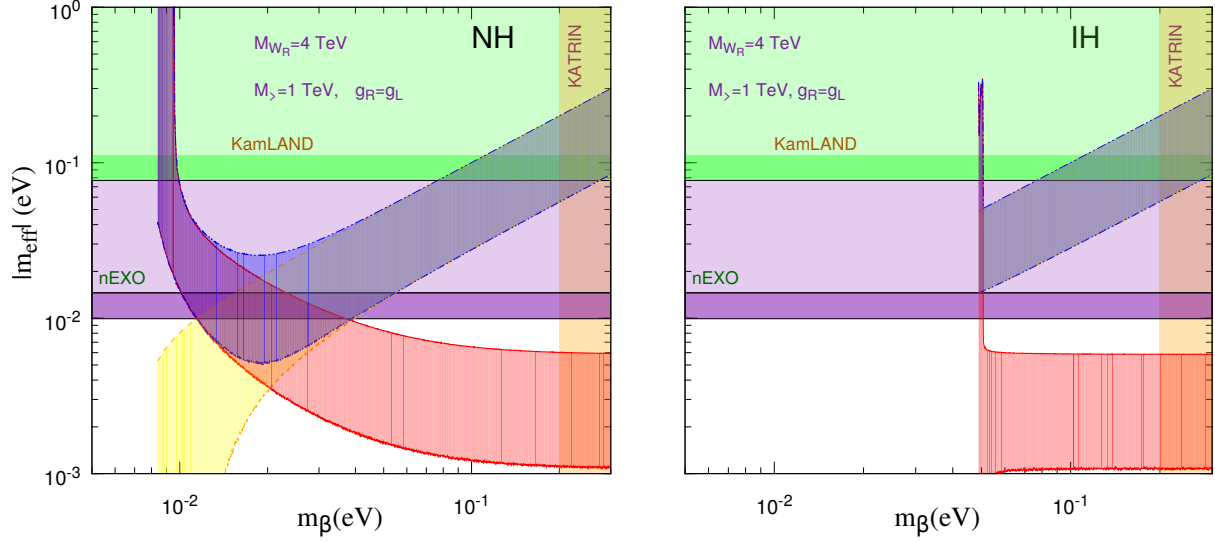


FIG. 3. The effective mass of $0\nu\beta\beta$ vs the effective mass of β -decay. The yellow and red region correspond to the light neutrino exchange and RR contribution. The blue region represents the total contribution. The future ton-scale experiment nEXO can rule out the IH scenario for the adopted benchmark points.

$ m_{ee}^\nu $ and other BSM factors	Limits for ^{136}Xe		
Canonical: [eV]	Argonne	intm	0.114
		large	0.095
$ m_{ee}^\nu = \sum_i U_{ei} m_i $	CD-Bonn	intm	0.089
		large	0.078
RR: [TeV^{-5}]	Argonne	intm	0.080
		large	0.082
$\frac{1}{M_{WR}^4} \left \sum_i \frac{V_{ei}^{*2}}{M_i} \right $	CD-Bonn	intm	0.078
		large	0.076
LL: [TeV^{-1}]	Argonne	intm	3.34×10^{-6}
		large	3.42×10^{-6}
$\left \sum_i \frac{S_{ei}^{*2}}{M_i} \right $	CD-Bonn	intm	3.28×10^{-6}
		large	3.17×10^{-6}
Right triplet: [TeV^{-5}]	Argonne	intm	4.54×10^{-4}
		large	4.65×10^{-4}
$\frac{1}{m_{\delta_R}^2 M_{WR}^4} \sum_i V_{ei}^2 M_i $	CD-Bonn	intm	4.46×10^{-4}
		large	4.32×10^{-4}
λ exchange: [TeV^{-2}]	$(3.18 - 4.05) \times 10^{-5}$		
$\frac{1}{M_{WR}^2} \sum_i U_{ei} T_{ei}^* $			
η exchange:	$(1.22 - 1.38) \times 10^{-9}$		
$\tan \xi \sum_i U_{ei} T_{ei}^* $			

TABLE III. The limits on the effective mass m_{ee}^ν and other relevant BSM parameters for LR symmetry that satisfy KLZ [39]. For all exchange mechanisms, other than λ and η , we consider the NME from [56]. For λ and η , we follow [7, 47].

inance, such as, LL, η , λ or Higgs triplet contribution, we show the limits on the particle physics parameters in

Table. III (for ^{136}Xe) and for ^{76}Ge in Table. VI.

While an individual measurement of $0\nu\beta\beta$ alone is not sufficient to conclusively point out the dominant mechanism behind this, the correlation of several other observables, such as observable for β decay, the cosmological masses and the effective mass of $0\nu\beta\beta$ together might be indicative [48]. In Fig. 3, we show the correlation between the effective mass of light and heavy neutrino exchange in $0\nu\beta\beta$ and the observable of β decay. The yellow and pink regions represent the predictions for the light neutrino exchange and the RR exchange mechanisms in $0\nu\beta\beta$. Note that, for Type-II dominance and for mass of RH neutrino $M_{>} = 1 \text{ TeV}$, there is no other contributions in β decay. This is also evident from this figure, that the Type-II IH scenario can be completely ruled out by the ton scale experiments nEXO.

Note that, the weak gauge couplings of LR model may be different ($g_R \neq g_L$) if LR symmetry does not preserve the D-parity [65, 66]. An independent verification of $g_R \neq g_L$ in $0\nu\beta\beta$ is therefore necessary to carry out. In Fig. 4, we show the parameter space in $g_R - M_{WR}$ plane that saturates the KLZ limit and the projected sensitivity of nEXO, assuming the heavy neutrino mass $M_{>} = 1 \text{ TeV}$, and $f_L = f_R$ for simplicity. In deriving the limits, we consider both the canonical contribution and RR together. We set the light neutrino masses $m_{<} \approx$ near quasi degenerate regime 0.0567 eV that saturates the PLANCK limit $m_\Sigma = 0.17 \text{ eV}$ [38] and hierarchical regime 10^{-4} eV . The green (NH) and purple (IH) points represent the allowed-parameters that saturate KLZ limit for $m_{<} = 0.0567 \text{ eV}$. Note that in quasi-degenerate

regime where the dominant contribution comes from light neutrino exchange, the two scenarios overlap, making this difficult to determine the hierarchy. The red (IH) and orange (NH) points represent the allowed-parameters that saturate the KLZ limit for much hierarchical mass regime $m_{\chi} = 10^{-4}$ eV, that is clearly separable. The blue dots correspond to optimal nEXO sensitivity. Note that, for the quasi-degenerate light neutrino mass, the total contribution from canonical and RR exchange can be ruled out for much less sensitivity of nEXO, and hence does not show up in the figure where we have considered $T_{1/2}^{0\nu} = 6.6 \times 10^{26}$ yrs. The same happens for IH hierarchical scenario. For each of the selected light neutrino mass, the band in the $g_R - M_{W_R}$ plane corresponds to the variation of the oscillation parameters in their 3σ region [1]. In addition, we also include the NME variation [56].

Note that, although we have explored the limits from $0\nu\beta\beta$, there are other relevant seahces, namely, the di-jet searches at LHC for W' [27], the same sign dilepton searches [29, 30] give stringent constraints on the masses of the gauge boson W_R and heavy neutrino N and. For a summary of relevant searches, see [28]. The updated 13 TeV dijet search from ATLAS (assuming 75% branching ratio for $W' \rightarrow jj$ and an SM like coupling) rules out the W_R mass upto 2.9 TeV [27]. For $M_N < M_{W_R}$, this search has a very minor dependency on the mass of N (through branching ratio). Assuming that the W_R couples to two light generation of quarks through CKM type mixing, the branching ratios to different states become: $\text{Br}(W \rightarrow eN) = 10\%$, $\text{Br}(W_R \rightarrow jj)$ and $\text{Br}(W_R \rightarrow tb)$ as

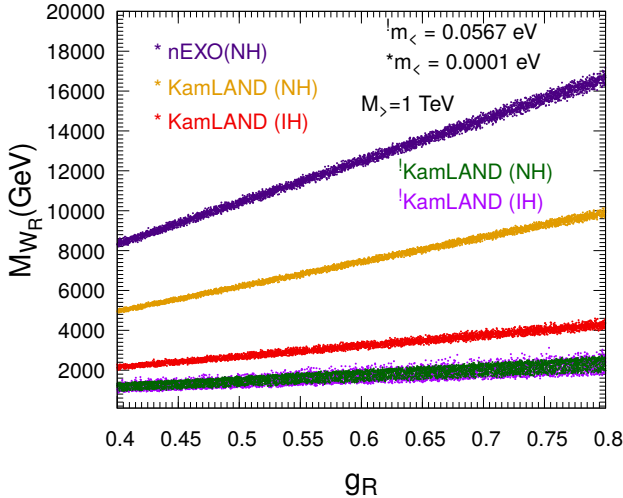


FIG. 4. The variation of M_{W_R} vs the gauge coupling g_R , that satisfy the KLZ bound [39] and the future sensitivity of nEXO [60].

60% and 30%, respectively [67]. For 60% branching ratio, the limit is similar $M_{W_R} \sim 2.8$ TeV. On the other hand, the search from same-sign dilepton constrains the TeV-hundred GeV $M_{W_R} - M_N$ mass plane. The 95% C.L limit from ATLAS 8 TeV search on the M_{W_R} reaches 2.9 TeV for heavy neutrino mass $M_N = 50$ GeV [29] (see Fig. 11 and Table. 6 of [29] for a scan over parameter space). For all the mediators M_{W_R} and M_N in the TeV-few hundred GeV mass range, the LHC same sign lepton search is most constraining and even gives much more stringent limits than $0\nu\beta\beta$ [68]. However, for lower N masses, such as only few GeV, or MeV and the other mass range where $M_N > M_{W_R}$, the LHC same sign dilepton search is not applicable [9], therefore allowing a huge range of parameters, where $0\nu\beta\beta$ can be more informative.

Below, we discuss the other BSM scenario RPV susy.

R-Parity Violation: The RPV superpotential with the λ' coupling is

$$W_R = \lambda' L Q d^c. \quad (11)$$

This induces the following Lagrangian terms,

$$\mathcal{L} = -\lambda'_{ijk} \tilde{l}_i u_j d_k^c - \lambda'_{ijk} \tilde{u}_j l_i d_k^c + \lambda'_{ijk} \tilde{d}_j \nu_i d_k^c + \tilde{\nu}_i d_j d_k^c + \dots \quad (12)$$

The $0\nu\beta\beta$ process receives contribution from neutrino-sbottom exchange - via λ'_{113} , λ'_{131} couplings, squark-gluino exchanges - via λ'_{111} coupling [16–21, 24]. Here, we update the bounds on the relevant dimensionless parameters $\eta_{\tilde{q}}$ (relevant for sbottom exchange) and $\eta_{\tilde{g}}$ following the KLZ result.

- neutrino-squark contribution depends on the squark masses and the product of couplings $\lambda_{113}\lambda_{131}$. The dimensionless parameter for sbottom exchange is, $\eta_{\tilde{b}} = \frac{\lambda'_{113}\lambda'_{131}}{2\sqrt{2}G_F} \sin 2\theta \left(\frac{1}{m_{\tilde{b}_1}^2} - \frac{1}{m_{\tilde{b}_2}^2} \right)$, where θ is the mixing between left and right handed chiral sbottom states \tilde{b}_L and \tilde{b}_R . The masses of the physical sbottom states are $m_{\tilde{b}_1}$ and $m_{\tilde{b}_2}$, respectively. Similar to the sbottom exchange, other squarks can also contribute in this process.
- The gluino exchange can give large contribution in $0\nu\beta\beta$. Assuming, the gluino and the squarks as the mediators, the relevant dimensionless parameter $\eta_{\tilde{g}}$ is $\eta_{\tilde{g}} = \frac{\pi\alpha_s}{6} \frac{\lambda'^2_{111}}{G_F^2 m_{\tilde{d}_R}^4} \frac{m_p}{m_{\tilde{g}}}$, where for simplicity we have assumed down-type squark exchange gives large contribution. Similar contribution can be obtained from up-type squark exchange.

In Table. IV, we provide the updated limits on the dimensionless parameters $\eta_{\tilde{b}}$ and $\eta_{\tilde{g}}$. The limits corresponding to GERDA Phase-II measurements are given in Table. VII. In Fig. 5, we show the constraints on $\lambda_{113}\lambda_{131}$ with respect to sbottom mass variation, that

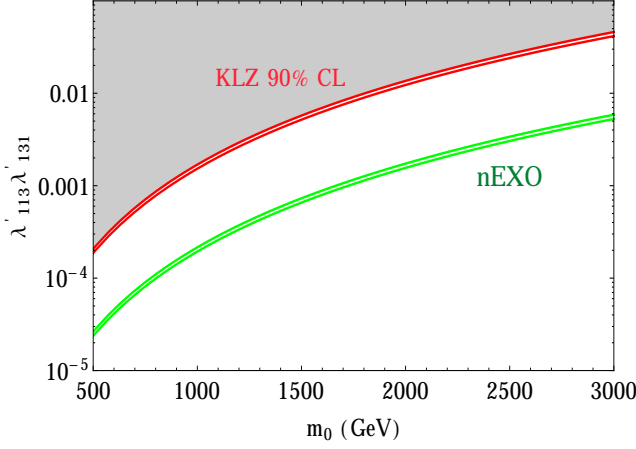


FIG. 5. The variation of $\lambda'_{113}\lambda'_{131}$ vs the common sbottom mass m_0 that satisfy the KLZ bound [39] and saturate the future sensitivity of nEXO [60]. The different of the sbottom mass from m_0 is 60 GeV and the mixing $\sin 2\theta = 10^{-4}$.

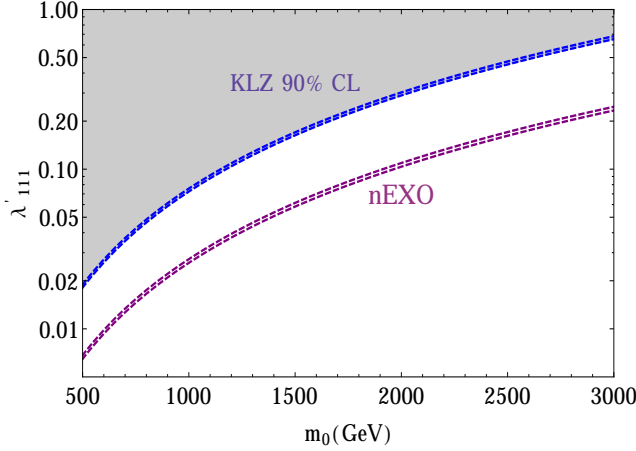


FIG. 6. The variation of λ'_{111} vs the down type squark mass m_0 that satisfy the KLZ bound [39] and saturate the future sensitivity of nEXO [60]. The gluino mass has been set to 2.0 TeV.

satisfies KLZ limits and saturates the nEXO sensitivity. We consider the two sbottom masses $m_{\tilde{d}_1, \tilde{d}_2} = m_0 \pm \Delta m$, with the mass difference being $\Delta m = 60$ GeV and the mixing $\sin 2\theta = 10^{-4}$. The gray shaded region is ruled out by the KLZ limit. In Fig. 6 we show the limit on the λ'_{111} that corresponds to the gluino-down type squark exchange. The green/purple band represent the sensitivity of the future ton-scale experiment nEXO that can probe much lower regime of couplings $\lambda_{113}\lambda_{131}/\lambda'_{111}$. In the analysis on RPV, we have not considered the effect of RG running. The gluino and squark exchange diagram will lead to operator mixing (tensorial and pseudoscalar). The QCD corrections to the coefficients of pseudo-scalar effective operator are large while for

tensorial operators, the correction is not significant as shown in [64]. Complete analysis including mixing between pseudoscalar and tensor operator would be more involved and will be considered in future work.

RPV	Limits for ^{136}Xe		
η_b	Argonne	intm	1.23×10^{-9}
		large	1.23×10^{-9}
	CD-Bonn	intm	1.24×10^{-9}
		large	1.12×10^{-9}
$\eta_{\tilde{g}}$	Argonne	intm	1.20×10^{-9}
		large	1.20×10^{-9}
	CD-Bonn	intm	1.21×10^{-9}
		large	1.11×10^{-9}

TABLE IV. The limits on the RPV dimensionless parameters from KLZ [39]. We adopt the NME from [56].

Before conclusion, we would like to make some remarks about the searches for RPV at colliders. Introducing non-zero RPV coupling generally weakens up the mass and cross-section limits for the sparticles. The summary of the searches can be found in [32], where the main focus is on pair production of squarks and gluinos, and their further decays. Several searches have been conducted for RPV λ'' , λ' and λ couplings. Limits have been set on the gluino mass $m_{\tilde{g}} \geq 1550$ GeV, where gluino decays to hadronic final states [33] via via neutralino $\tilde{\chi}^0$ and λ'' coupling. On the other hand, for λ coupling, searches have been conducted for fully leptonic channel [34], originating from chargino decays. In the most constraining scenario, chargino mass upto 1.14 TeV have been excluded. The limit weakens for large mass hierarchy between chargino and lightest neutralino mass, where the decay products are boosted [34]. For a summary of Run-1 search see [32]. For λ' searches, a) searches for the third generation of squarks $pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow b\bar{b}l\bar{l}$ constrain stop mass 1 TeV, where \tilde{t} decays to b quark and e [35], b) searches for multilepton and b-jet constrain \tilde{t} mass 1 TeV [36] (relevant for λ'_{233} and λ'_{231}). c) final states with τ and b-jets (relevant for λ'_{333} and λ'_{3jk}) [37]. For this search, assuming a 100 % branching ratio, mass limits have been set on stop mass as 580 GeV. Note that none of these above searches distinguishably constrain λ'_{111} or λ'_{131} coupling. However, if more than one RPV coupling is present, then the above mentioned searches will be relevant. In [32], the channel that has been analysed is $pp \rightarrow \tilde{g}\tilde{g} \rightarrow \tilde{\chi}_1^0 qq \tilde{\chi}_1^0 qq$ and $pp \rightarrow \tilde{q}\tilde{q} \rightarrow \tilde{\chi}_1^0 qq \tilde{\chi}_1^0$ with $\tilde{\chi}_1^0 \rightarrow l/\nu qq$. In most of the cases, this set limit on squark/gluino mass $m_{\tilde{g}}/m_{\tilde{q}} > 1$ TeV. We consider the gluino mass \tilde{g} as 2 TeV in our analysis. The parameter space shown in Fig. 5 and Fig. 6 is consistent with the present LHC searches.

Conclusion— In the light of the recent results from

KamLAND-Zen and GERDA Phase-II, we update limits on the effective mass and new physics parameters for $0\nu\beta\beta$ considering two widely discussed BSM scenarios, Left-Right symmetry and RPV susy. The recent KLZ limit puts stringent constraint on the effective mass for light neutrino exchange $m_{ee}^\nu \leq 0.06 - 0.14$ eV, almost factor of two improvement as compared to the previous limit. We re-check the validity of the positive claim against the null result of KLZ and find that assuming the light neutrino exchange is the only mechanism of $0\nu\beta\beta$, the recent KLZ and GERDA Phase-II limits individually rule out the positive claim of observation completely, for all NME. In the BSM scenarios, our findings are i) the KLZ limit provides factor of two improvement for the BSM parameters ii) For Type-II dominated Left-Right model, a wide range of RH neutrino mass is now excluded. We show this explicitly for the RH gauge boson mass ≤ 4 TeV and the heaviest RH neutrino mass 1 TeV. This leaves very limited parameter space to probe distinguishable BSM contribution that comes from RR exchange. iii) For the RPV susy, couplings of order $\mathcal{O}(0.01 - 0.1)$ is ruled out from KLZ for sbottom/squark mass between 500 GeV-3 TeV iv) We show that the next generation ton scale experiment nEXO will be able to rule out distinguishable BSM signature for $M_{W_R} \leq 4$ TeV in NH scenario and will be able to completely rule out IH scenario for BSM as well as Standard $0\nu\beta\beta$ contribution. For RPV scenarios, nEXO can probe $< \mathcal{O}(10^{-2})$ couplings.

APPENDIX

The bounds on RH neutrino masses corresponding to Fig. 2 and Table II but, for $g_R = 0.5$ are summarized in this table.

Acknowledgments– M.M acknowledges the hospitality of IPPP, Durham University, UK, where this work has been completed. The work of M.M is partially supported by the DST INSPIRE Grant INSPIRE-15-0074.

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NH			
M_{W_R}	2.5 TeV	3.0 TeV	3.5 TeV
$g_R = 0.5$			
$m_{<} \text{ (eV)} \gtrsim$	2.8×10^{-3}	1.4×10^{-3}	8×10^{-4}
$M_{<} \text{ (GeV)} \gtrsim$	54.8	27.4	15.7
$m_{<} \text{ (eV)} \lesssim$	3×10^{-8}	6×10^{-8}	10^{-7}
$M_{<} \text{ (MeV)} \lesssim$	0.6	1.2	2.1
IH			
M_{W_R}	2.5 TeV	3.0 TeV	3.5 TeV
$g_R = 0.5$			
$m_{<} \text{ (eV)} \gtrsim$	9×10^{-5}	4×10^{-5}	2×10^{-5}
$M_{<} \text{ (GeV)} \gtrsim$	1.8	0.8	0.4
$m_{<} \text{ (eV)} \lesssim$	9×10^{-7}	2×10^{-6}	4×10^{-6}
$M_{<} \text{ (MeV)} \lesssim$	18.7	41.6	83.3

TABLE V. The bounds on the RH and lightest neutrino masses from KLZ [39]. In NH case lightest right handed neutrino $M_{<}$ is either lighter than 0.6/1.2/2.1 MeV or heavier than 54.8/27.4/15.7 GeV for $M_{W_R} = 2.5/3/3.5$ TeV and $M_{>} = 1$ TeV. Similarly, In IH case $M_{<}$ is either lighter than 18.7/41.6/83.3 MeV or heavier than 1.8/0.8/0.4 GeV for $M_{W_R} = 2.5/3/3.5$ TeV and $M_{>} = 1$ TeV.

$ m_{ee}^\nu $ and other BSM factors	Limits for ^{76}Ge		
Canonical: [eV]	Argonne	intm	0.196
		large	0.172
$ m_{ee}^\nu = \sum_i U_{ei} m_i $	CD-Bonn	intm	0.183
		large	0.160
RR: [TeV $^{-5}$]	Argonne	intm	0.200
		large	0.176
$\frac{1}{M_{W_R}^4} \left \sum_i \frac{V_{ei}^{*2}}{M_i} \right $	CD-Bonn	intm	0.133
		large	0.113
LL: [TeV $^{-1}$]	Argonne	intm	8.36×10^{-6}
		large	7.35×10^{-6}
$\left \sum_i \frac{S_{ei}^{*2}}{M_i} \right $	CD-Bonn	intm	5.54×10^{-6}
		large	4.73×10^{-6}
Right triplet: [TeV $^{-5}$]	Argonne	intm	4.58×10^{-4}
		large	9.99×10^{-4}
$\frac{1}{m_{\delta_R}^2 - M_{W_R}^4} \left \sum_i V_{ei}^2 M_i \right $	CD-Bonn	intm	7.54×10^{-4}
		large	6.43×10^{-4}
λ exchange: [TeV $^{-2}$]	$(1.61 - 7.51) \times 10^{-5}$		
$\frac{1}{M_{W_R}^2} \sum_i U_{ei} T_{ei}^* $			
η exchange:	$(2.87 - 7.77) \times 10^{-9}$		
$\tan \xi \sum_i U_{ei} T_{ei}^* $			

TABLE VI. The limits on the effective mass m_{ee}^ν and other relevant BSM parameters for LR symmetry that satisfy GERDA-II [42]. For all exchange mechanisms, other than λ and η , we consider the NME from [56]. For λ and η , we follow [7, 47].

RPV	Limits for ^{76}Ge		
$\eta_{\tilde{g}}$	Argonne	intm	3.07×10^{-9}
		large	2.54×10^{-9}
	CD-Bonn	intm	2.98×10^{-9}
		large	2.51×10^{-9}
$\eta_{\tilde{g}}$	Argonne	intm	3.11×10^{-9}
		large	2.61×10^{-9}
	CD-Bonn	intm	3.55×10^{-9}
		large	3.07×10^{-9}

TABLE VII. The limits on the RPV dimensionless parameters from GERDA Phase-II [42]. We adopt the NME from [56].

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